IS THERE A SUPERMASSIVE BLACK HOLE IN THE NUCLEUS OF M31?

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The observations covered by this grant were the first in a long-term monitoring program of the center of M31 in both x-rays and radio. Coordinated VLA observations were conducted during these observations, and the x-ray and radio results were reported at the American Astronomical Meeting in January, 1995. These included a marginal detection of anti-correlated variability between the radio and x-ray sources at the nucleus of M31, as predicted by the supermassive black hole model. This was a promising start, but further progress requires additional coverage in both x-ray and radio. Additional observations were, indeed, obtained during the ROSAT AO-6 observing season, and are covered under contract NAG5-3210. However, before continuing in the program, we felt compelled to address the question of the reality of the association between the radio and x-ray sources, given the relatively large error circle for the latter. As detailed in the attached paper draft, we therefore reanalysed earlier Einstein and ROSAT observations of the region, as well as the observations covered in the current contract and under NAG5-3210, in an attempt to reduce the uncertainty of the x-ray position. We were successful in doing so, and find that the radio source remains within the much smaller x-ray error circle. Although the identification cannot be guaranteed, we find that the association between the x-ray and radio sources remains probable and further work on coordinated x-ray and radio observations is justified. Further results in this program will be reported under contract NAG5-3210.

ABSTRACT

We have determined a more accurate position for the x-ray source near the nucleus of M31, based on analysis of new ROSAT HRI observations and re-analysis of earlier ROSAT and HRI observations of the region. We find a revised position of $0^h42^m44^s31$, $41°16'06''7$ (J2000), with a 90% error radius of $1''3$. Although this error circle formally excludes the nuclear radio source reported by Crane, Dickel, and Cowan, the radio source *is* included in the 99% x-ray error circle, and given the residual systematic uncertainties in the x-ray astrometry, we consider the association of the x-ray and radio sources to be still viable. Analysis of the superposition of three deep, ROSAT HRI observations also indicates the presence of a previously uncataloged source, approximately $17''$ to the east of the nuclear source.

Subject headings: X-rays: galaxies — galaxies: individual: M31 — galaxies: nuclei

1. Introduction

X-ray emission in the vicinity of the M31 nucleus has been extensively studied with high-resolution imaging instruments (HRI's) on board both the Einstein and ROSAT Observatories (Van Speybroeck et al. 1979; Trinchieri and Fabbiano 1991; Primini, Forman, & Jones 1993). A number of discrete (i.e. unresolved) x-ray sources have been detected, together with a faint, extended component, attributable to either the superposition of fainter, discrete sources or a truly diffuse component. A persistent discrete source, located $\sim 2''$ from the nucleus, has been suggested as the nuclear x-ray counterpart by van Speybroeck et al. (1979). This source is the subject of renewed interest due to the detection of an unresolved, variable, radio source (Crane, Dickel, & Cowan 1992; Crane et al. 1993) coincident with the dynamical center inferred from high-resolution observations of M31's rotation curve and velocity dispersion distribution (Dressler & Richstone 1988; Kormendy 1988). These dynamical measurements indicate the presence of a massive ($\sim 10^7$ $M_\odot$) object at the center of M31. If the x-ray and radio emission originate from the same object, then repeated, coordinated radio and x-ray observations would provide strong constraints on models for the source (Melia 1992).

We have been engaged in such a monitoring campaign since 1994, using both the ROSAT HRI and the VLA. We will report the results of our campaign in a later paper, but here we address the question of the association of the x-ray and radio sources. To date, the only basis for the association is positional coincidence. However, the $\sim 3''.2$ 90% error circle radius of the Einstein HRI (Harris 1984) and the $\sim 2''.5$ error radius of the ROSAT HRI (Primini, Forman, & Jones 1993) are relatively large, and there is a significant ($\sim 10\%$) chance of finding a bright ($\sim 5 \times 10^{36}$ erg s^{-1}) x-ray source, at random, within $\sim 5''$ of the nucleus, given the local x-ray source density (Van Speybroeck et al. 1979). Moreover, the ROSAT and Einstein positions for the x-ray source differ by $3''.7$ (Trinchieri and Fabbiano 1991; Primini, Forman, & Jones

1993); because of the high degree of variability in many of the x-ray sources in M31 and the suspected presence of a higher density of fainter sources, the possibility that the Einstein and ROSAT sources are, in fact, different cannot be discounted. The association of the x-ray source and the radio source is thus far from certain.

In an attempt to address this uncertainty, we have reanalysed the original Einstein and ROSAT HRI observations, together with new ROSAT HRI observations at three different epochs, in a consistent manner, using the x-ray emitting globular clusters to perform the astrometry. In addition, we have superposed the data from all deep ROSAT observations of the center of M31 to search for fainter x-ray sources near the nucleus. In the next section, we discuss the details of the observations and astrometry. Our results on the position of the x-ray source near the nucleus are presented in section 3, and the results of the analysis of the superposed image in section 4. We conclude that the Einstein and ROSAT sources are indeed the same, with an average position consistent with the radio source, and with a much-reduced error radius. Although a previously undetected source is found $\sim 16''$ to the east, no other fainter x-ray sources are detected near the nucleus.

2. Observations and Analysis

The observations used in the current analysis are listed in Table 1. To improve sensitivity, we have combined multiple observations at a given epoch into single images, using the persistent, bright source at $0^h 42^m 39^s$, $41°16'03''$ as a reference. We have searched each image for discrete sources, using the IRAF/PROS $ldetect$ task with a $12''$detect cell, and, with the exception of the 1995 image, included only those sources with a count rate significance $\gtrsim 5\sigma$ for further analysis. The exposure in the 1995 image was too low to detect a sufficient number of $\gtrsim 5\sigma$ x-ray emitting globular clusters for astrometric analysis, and we were forced to reduce the acceptable count rate significance to 3σ. We include results for this epoch for

illustrative purposes but do not include it in the calculation of average position.

We then matched sources detected in each epoch with globular cluster positions from both the MIT catalog (Magnier et al. 1995) and the Bologna catalog (Battistini et al. 1987). Our selection criterion is positional coincidence of $\lesssim 10''$, but typically, the separation between the x-ray and optical positions is much better than this. We then use x-ray centroids in pixel coordinates and the celestial positions for the corresponding globular clusters to compute the astrometric solution for each image, using the IRAF/CTIO *coords* task. Finally, we apply this solution to the x-ray pixel coordinates of the source near the nucleus to arrive at its celestial coordinates.

We have matched globular clusters in both catalogs and find 126 common sources within $\sim 30'$ of the nucleus of M31. Right Ascension and Declination offsets for these clusters are shown in Figure 1, and indicate a small systematic offset between MIT and Bo coordinates of $0\rlap{.}''84 \pm 0\rlap{.}''07$ in Right Ascension and $0\rlap{.}''11 \pm 0\rlap{.}''04$ in Declination. Therefore, we do not, in general, combine matches from both catalogs, but perform separate astrometric reductions for each catalog. The one exception to this is the Einstein HRI image, for which there were too few matches from the MIT catalog alone to provide an astrometric solution. Again, we show these results below for illustrative purposes but do not include them in the calculation of final positions.

Finally, we have combined data from the 1990, 1994, and 1996 epochs into a single image, again using the same bright x-ray source as a reference, and applied the above analysis procedures to it, with the exception that we used a smaller, $9''$ detect cell, to restrict the region used for x-ray centroiding of sources in the crowded nuclear region.

3. The Position of the X-ray Source Nearest the Nucleus

Our results for the x-ray position of the source near the nucleus, for each epoch, and for each globular cluster catalog are shown in Table 2. The 90% error radii include both the astrometric error (i.e., the rms of the offsets between predicted and actual positions for the globular clusters) and the statistical error in determining the centroid of the x-ray source. We note, in general, systematic offsets between the positions of the x-ray source as determined from the two different catalogs. As discussed above, we calculate the average position using epochs 1979-1980, 1990, 1994, & 1996 for the Bologna catalog, and epochs 1990, 1994, & 1996 for the MIT catalog. We find, using the Bo catalog, an average x-ray position of $\alpha_{Bo} = 0^h 42^m 44\overset{m}{.}38$, $\delta_{Bo} = 41°16'06\overset{''}{.}6$, with a 90% error radius of $r_{90} = 1\overset{''}{.}4$. Using the MIT catalog, we find $\alpha_{MIT} = 0^h 42^m 44\overset{m}{.}31$, $\delta_{MIT} = 41°16'06\overset{''}{.}7$, with $r_{90} = 1\overset{''}{.}3$. These results are shown in Figure 2.

4. Other X-ray Sources in the Vicinity

A image of the central $\sim 4'$ of M31, obtained from summation of the ROSAT data for epochs 1990, 1994, and 1996, is shown in Figure 3. The image has been smoothed with a $3''$ gaussian, and totals $\sim$179 kec in exposure, nearly 4 times deeper than the original 1990 exposure (Primini, Forman, & Jones 1993). We estimate a limiting sensitivity of $\sim 10^{36}$ erg s^{-1}. The nuclear source is labelled source 2. Source 1 is a previously uncataloged x-ray source at $0^h 42^m 45\overset{m}{.}8$, $41°16'07\overset{''}{.}0$. All other sources have been previously detected in either Einstein or ROSAT observations. There is no evidence for elongation of contours in the vicinity of the nuclear source, that might indicate the presence of an underlying source sufficiently close to the nucleus to explain the original, discrepant Einstein and ROSAT positions.

5. Conclusions

A reanalysis of data from all high resolution x-ray observations of the nuclear region of M31 has reduced the area of the error circle for the x-ray source associated with the nucleus by a factor of ~ 4. Individual position measurements are all consistent with a single source, and although the formal 90% error circle does not include the nuclear radio source, the 99% confidence error circle does. Moreover, a systematic astrometric uncertainty of a few tenths of an arcsecond is quite likely, depending on the globular cluster catalog used. No evidence for fainter x-ray sources near the nucleus, which could confuse the identification of the nuclear x-ray source has been found, to a limit of $\sim 10^{36}$ erg s^{-1}. We conclude that the identification of the x-ray source with the radio source remains probable. We note that the limiting factor in this analysis is the astrometric uncertainties in the optical globular cluster catalogs. This is likely to remain the case even with the increased spatial resolution of AXAF. In the end, confirmation of the identification may depend on continued radio and x-ray monitoring, to detect phenomena such as correlated x-ray and radio variability.

Table 1. Observation Log

Observatory	Sequence(s)	Epoch	Total Exposure
Einstein	579, 4479, 7066	1979-1980	65 ksec
ROSAT	150006	1990	48
ROSAT	600474n00, 600475n00	1994	46
ROSAT	600674n00, 600675n00	1995	9
ROSAT	400780n00	1996	85

Table 2. Celestial Position of X-ray Source Near Nucleus of M31

Epoch	α_{Bo}	δ_{Bo}	r_{90}	α_{MIT}	δ_{MIT}	r_{90}
1979-1980[a]	0:42:44.45	41:16:08.0	$2\overset{''}{.}9$	0:42:44.41	41:16:07.7	$3\overset{''}{.}2$
1990	0:42:44.34	41:16:05.6	2.9	0:42:44.28	41:16:06.3	2.7
1994	0:42:44.35	41:16:06.3	2.5	0:42:44.30	41:16:06.7	1.9
1995[b]	0:42:44.33	41:16:09.3	2.0	0:42:44.29	41:16:09.7	3.0
1996	0:42:44.39	41:16:06.6	3.0	0:42:44.36	41:16:07.0	2.4

[a]Not used in calculation of average MIT position

[b]Not used in calculation of average MIT or Bo position

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Fig. 1.— Right Ascension and Declination offsets for 126 globular clusters listed in both the MIT and Bo catalogs.

Fig. 2.— Location of the x-ray source as determined by both the Bo and MIT catalogs. The small cross at zero offset marks the location of the optical nucleus BD+40°148 and the small circle $\sim 5''$ to the west is the error circle for the radio source. Both 90% (solid) and 99% (dashed) error circles are shown at the MIT and Bo positions.

Fig. 3.— Superposition of ROSAT data from 1990, 1994, and 1996 epochs, smoothed with a $3''$ gaussian. The total exposure is $\sim$179 ksec. The nuclear source is source 2.